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Simulating the Annual Energy Yield of a Rotationally Asymmetrical Optical Concentrator

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***Abstract*— This paper simulates the annual energy yield of a concentrator called the rotationally asymmetrical dielectric totally internally reflective concentrator (RADTIRC). One specific design of the RADTIRC is assumed to be installed in Berlin/Brandenburg, Germany. Simulation and experimental work have been carried out to determine the optical concentration gain under direct and diffuse radiations. Based on the analysis, it was found that the yearly energy yield was increased by a factor of 2.29 when the RADTIRC-PV module was used when compared with the non-concentrating PV module.**

Keywords — solar photovoltaic; building integrated photovoltaic systems; rotationally asymmetrical dielectric totally internally reflecting concentrator; annual output; Berlin.

I. Introduction

In the last 10 years, solar photovoltaic (PV) has seen a significant growth around the globe. Solar PV added an additional capacity of 75 GW in 2016, making it reached a new cumulative installation of 303 GW [1]. With a continuous huge investment in solar technology totalling to $1133.6 billion from 2006 until 2016, this technology has created around 3.1 million jobs worldwide, which corresponds to 31% of the renewable energy job markets in 2016 [1].

In spite of the oversupply and decreasing prices of PV modules, the cost to install a PV system is still perceived as 'very expensive' in many countries. Based on the International Energy Agency Photovoltaic Power System Programme (IEA-PVPS) analysis, the PV module contributed between 40% and 50% of the total cost of installation [2]. The cost of installation plays a critical role in attracting consumers to install any solar PV system [3]. It is imperative to bring the installation cost further down to incentivise more installations. This will help to further push the contribution of solar PV in satisfying the global electricity need from only 1.2% [2] at the moment to a much greater percentage.

One of the ways of lowering the cost is by reducing the amount of expensive PV material that dominates up to 73% [4] of the PV module cost, i.e. the PV material represents as high as 36.5% of the overall cost of installation. In order to minimise the amount of PV material whilst maintaining the electrical output from the PV module, some researchers proposed to integrate a solar concentrator in the PV module [5], [6], producing a concentrating PV (CPV) system. Interestingly, besides focusing on devising the best concentrator for a power plant, the research also started to pay more attention to the usage of concentrators for building integration applications [7]–[10], researching specifically on the low concentration concentrator. The combination of a low concentration photovoltaic (LCPV) structure for building integration is known as building integrated concentrating photovoltaic (BICPV) system.

The concentrator investigated in this paper is called the rotationally asymmetrical dielectric totally internally reflecting concentrator (RADTIRC). It focuses on the formulations to predict the annual electrical output of an RADTIRC-PV system installed in Berlin.

II. RADTIRC Design

The RADTIRC was first developed by Ramirez-Iniguez et al. [11] to provide a higher electrical output, thus minimising the usage of expensive PV material, and ultimately reducing the PV system cost [12]. The steps to produce the RADTIRC have been explained in detail by Ramirez-Iniguez et al. [11]. Muhammad-Sukki et al. [12] wrote a MATLAB code to help visualise and investigate the geometrical properties of the RADTIRC design. A variety of concentrators from this family have been created and simulated to evaluate their optical concentration gains [12]. The experimental results showed that

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the optimised design achieved an opto-electronic gain of 4.48 when compared to the bare cell [13]. Another analysis was performed to investigate the effect of diffuse radiation on the RADTIRC. Freier et al. [14], [15] concluded that the RADTIRC has an opto-electronic gain of 2.13 under diffuse radiation. A solar window that employed 12 RADTIRCs was also constructed and tested indoors, achieving a maximum opto-electronic gain of 4.13 when compared to a non-concentrating PV window (see Fig. 1) [16]. The panel was also tested outdoors for 4 days in Glasgow, United Kingdom in 2014. As expected, the RADTIRC-PV panel produced a higher short circuit current than the non-concentrating panel for sun rays captured within its half-acceptance angle [16]. Due to lack of equipment, the study did not differentiate the contribution from direct nor diffuse solar irradiance to the electrical output of the concentrator, rather it considered the total contribution from both components.

Having done all the tests, the data from simulations and experiments could be used to predict the annual performance of an RADTIRC-PV module. This information is crucial to the stakeholders since it demonstrates the viability of such system to become a substitute to the traditional non-concentrating PV system.

Fig. 1: An RADTIRC-PV window.

III. Simulation & Results

Skylights with PV modules are taken as an example to show where RADTIRC concentrators could be applied. In this paper, an annual prediction for such an application is carried out for Berlin/Brandenburg, Germany. The comparison between the CPV and PV modules in this analysis is based on the same volume of PV material being used. The standard dimensions of a solar panel are 540 mm x 1200 mm. By subtracting the frame of the module, the approximate active area of the PV module is 0.58 m^2. Referring to the manufactured CPV window sample, which has 7.1 times the area of the PV material used, it leads to a CPV module size of 4.1 m^2. However a skylight PV module is generally larger than a conventional PV module due to the gaps left between the cells for room illumination. The PV cell efficiency was determined experimentally and the measured value under standard test conditions was 14.9% [14].

In order to do the prediction, several key parameters need to be determined, which are: (i) tilt angle of the modules; (ii) optical concentration gain of the RADTIRC on tilted surface, and (iii) irradiation data. The ideal energy yield of the CPV module, E_{ideal}, was calculated using Equation 1 [17]:

$$E_{ideal} = A_{pv} * \eta_{pv} * H_{solar} * C_{opt} \quad (1)$$

where A_{pv} is the area of the PV material, η_{pv} is the solar cell efficiency, H_{solar} is the solar irradiation and C_{opt} is the optical concentration gain.

The yearly energy yield of the non-concentrating PV module was calculated to be 116.39 kWh whereas the RADTIRC-PV module had an increased output by a factor of 2.29 providing 266.26 kWh per year. Since the designed geometrical concentration gain is 4.91, the factor by which the output is increased is lower than desired. However, this can be justified by looking at the yearly irradiation of Berlin, where diffuse irradiation makes up to 58.7% of the global irradiation when summed over the year. As the determined optical concentration gain for diffuse irradiation is only 1.94, more than half of the yearly irradiance is concentrated with the low concentration factor. Fig. 2 shows the monthly energy yield for the RADTIRC-PV and the non-concentrating PV modules.

The largest energy yield is achieved with the RADTIRC-PV module in April and September even though the highest irradiance is during June and July. This is due to the fact that in April both the irradiance and the optical concentration are high. In September, when the angle of incidence is 0˚, the RADTIRC-PV module achieves the highest energy yield even though the irradiance is lower than in April. This shows the strong influence of the angle of incidence on the electrical output with regards to the solar altitude angle.

The performance of the concentrator during the year under direct and diffuse irradiance is shown in Fig. 2 as well. The calculated energy yield output of the RADTIRC-PV module subject to direct irradiance emphasises that being installed at a 53˚ tilt angle, the concentrator does not make the maximum use of the high irradiance during May to July. This is because the angle of incidence on the tilted module during these months is large. However, the concentration gain for the period April until August was taken to be lower than the actual value under real conditions. Looking at the performance of the concentrator under diffuse irradiance, the energy yield of the RADTIRC-PV module was nearly doubled throughout the year. In total, the energy yield from diffuse irradiation is 146 kWh and from direct irradiation 120 kWh per year. Again, it has to be considered that the estimated diffuse irradiation for Berlin is higher in percentage than the average value shown over the years from 2002 - 2004.

It has been shown that the annual energy yield of the RADTIRC-PV module for the location of Berlin/Brandenburg is more than doubled when compared to a conventional non-concentrating PV module. The best performance of the concentrators is during the months when the angles of incidence are ≤ 8˚ along the x-axis. The irradiation during the summer months is concentrated with a reduced optical concentration gain and cannot be entirely captured due to the reduced acceptance angle. During the winter months, the diffuse irradiance makes up a high percentage of the global irradiation and is concentrated with the lower concentration factor that was determined for diffuse irradiance. The overall result shows that for a location like Berlin/Brandenburg, the performance of the concentrator needs to be improved.

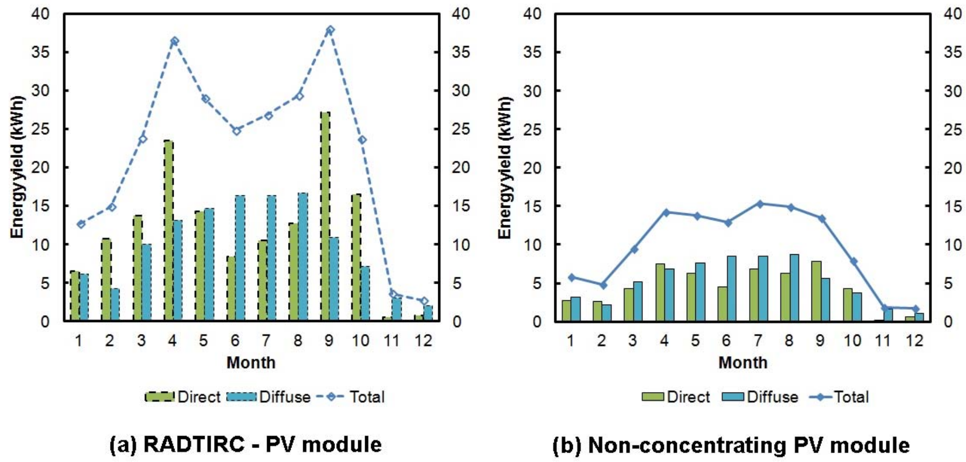

Fig 2. Comparison of the monthly energy yield between: (a) an RADTIRC-PV module, and (b) a non-concentrating PV module in Berlin.

CONCLUSIONS

The annual prediction of utilising an RADTIRC-PV module as a skylight installed theoretically in Berlin/Brandenburg, Germany was calculated and compared with a non-concentrating PV module. Based on the simulation results, it was found that the yearly energy yield was increased by a factor of 2.29 when the RADTIRC-PV system was compared with the non-concentrating counterpart. It has been shown that a tilt angle optimised for the month of the equinox reduces the performance of the concentrator during the summer months. To improve the performance of the concentrator, an increased half-acceptance angle of the concentrator or a different tilt angle of the system was suggested. The concentrator parameters also need to be adjusted to each location specifically depending on the irradiation and the longitude of the location. However, for a more exact prediction, the change of the sun altitude angle during the day needs to be considered yielding an improved concentration gain for each hour of the day. Also, losses must also be taken into consideration because it will reduce the performance of the RADTIRC. This include losses due to manufacturing errors, misalignment during assembly process, dust and soil accumulation, shadowing etc. [16], [18], [19].

As a conclusion, it has been demonstrated that the RADTIRC has the capability to improve the electrical output when compared with its non-concentrating counterpart that has the same amount of PV material. Taking into account the savings in PV material, increased natural illumination and potential heat generation, the attractiveness of implementing BIPV systems is increased. As a result, the BICPV technology can help achieve the EU target of having more zero carbon buildings, an improved technology efficiency and a higher share of energy generated from renewable sources.

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